COST-EFFECTIVENESS OF CONTROLLING EMISSIONS FOR VARIOUS ALTERNATIVE-FUEL VEHICLE TYPES, WITH VEHICLE AND FUEL PRICE SUBSIDIES ESTIMATED ON THE BASIS OF MONETARY VALUES OF EMISSION REDUCTIONS[1]

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ABSTRACT: Emission-control cost-effectiveness is estimated for ten alternative-fuel vehicle (AFV) types (i.e., vehicles fueled with reformulated gasoline, M85 flexible-fuel vehicles [FFVs], M100 FFVs, dedicated M85 vehicles, dedicated M100 vehicles, E85 FFVs, dual-fuel liquefied petroleum gas vehicles, dual-fuel compressed natural gas vehicles [CNGVs], dedicated CNGVs, and electric vehicles [EVs]). Given the assumptions made, CNGVs are found to be most cost-effective in controlling emissions and E85 FFVs to be least cost-effective, with the other vehicle types falling between these two. AFV cost-effectiveness is further calculated for various cases representing changes in costs of vehicles and fuels, AFV emission reductions, and baseline gasoline vehicle emissions, among other factors. Changes in these parameters can change cost-effectiveness dramatically. However, the rank of the ten AFV types according to their cost-effectiveness remains essentially unchanged.

Based on assumed dollars-per-ton emission values and estimated AFV emission reductions, the per-vehicle monetary value of emission reductions is calculated for each AFV type. Calculated emission reduction values ranged from as little as $500 to as much as $40,000 per vehicle, depending on AFV type, dollar-per-ton emission values, and baseline gasoline vehicle emissions. Among the ten vehicle types, vehicles fueled with reformulated gasoline have the lowest per-vehicle value, while EVs have the highest per-vehicle value, reflecting the magnitude of emission reductions by these vehicle types. To translate the calculated per-vehicle emission reduction values to individual AFV users, AFV fuel or vehicle price subsidies are designed to be equal to AFV emission reduction values. The subsidies designed in this way are substantial. In fact, providing the subsidies to AFVs would change most AFV types from net cost increases to net cost decreases, relative to conventional gasoline vehicles.

Introduction

To help tackle urban air pollution problems, various legislation and regulations have been proposed or adopted in the U.S. to introduce alternative-fuel vehicles (AFVs). Despite the legislative and regulatory activities promoting AFVs, few studies have been carried out to compare dollars-per-ton emission control cost-effectiveness among various AFV types. A recent study conducted by Wang et al. (1993) showed that AFV cost-effectiveness can vary

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significantly with different values for such parameters as AFV costs, AFV emission reductions, and baseline gasoline vehicle (GV) emissions. In their estimation, Wang et al. established two AFV cost cases (a high-cost case and a low-cost case) and two AFV emission-reduction cases (a low AFV emission-reduction case and a high AFV emission-reduction case) and presented ranges of AFV cost-effectiveness. They did not explicitly test the effect of individual cost and emission parameters on AFV cost-effectiveness.

On the basis of the model established by Wang et al., this paper estimates AFV cost-effectiveness with a set of base-case values for the various cost and emission parameters that determine AFV cost-effectiveness. Estimation of AFV cost-effectiveness with the base-case values is intended to show the differences in cost-effectiveness among various AFV types. Furthermore, a sensitivity analysis is conducted to test the importance of major emission and cost parameters in determining AFV cost-effectiveness. With the sensitivity analysis, AFV cost-effectiveness is calculated for various cases representing variations in values for major emission and cost parameters. The sensitivity analysis is intended to show the plausible range of cost-effectiveness for various AFV types.

To put AFVs into the economic cost/benefit perspective, this paper estimates the per-vehicle monetary value of emission reductions for various AFV types. AFV emission-reduction values are estimated from AFV life-cycle emission reductions and assumed dollar values per ton of emissions. AFV fuel or vehicle price subsidies are then designed to be equal to the calculated dollar values of AFV emission reductions. The fuel or vehicle subsidies designed in this way reflect society's willingness to pay for the use of AFVs for the sake of their emission reductions. Providing these subsidies will encourage use of AFVs, and therefore will help realize their emission-reduction benefits.

This paper addresses the following ten AFV types: GVs fueled with reformulated gasoline (RFG) (for presentation purposes, GVs fueled with RFG are named as an AFV type here), M85 flexible-fuel vehicles (FFVs), M100 FFVs, dedicated M85 vehicles, dedicated M100 vehicles, E85 FFVs, dual-fuel liquefied petroleum gas vehicles (LPGVs), dual-fuel compressed natural gas vehicles (CNGVs), dedicated CNGVs, and electric vehicles (EVs). GVs fueled with conventional gasoline are chosen here as the baseline vehicle to which the ten AFV types will be compared. In calculating vehicle emissions and costs, 1995 model-year compact passenger car projections are used in this paper; this implies that baseline GVs will meet the federal Tier 1 emission standards.

Input Parameters for AFV Cost-Effectiveness Calculation

This section presents the cost-effectiveness model developed by Wang et al. and the base-case values for emission and cost parameters used in this paper (for details of the model, see Wang et al. [1993]).

Emission-control cost-effectiveness of a particular AFV type is calculated from the life-cycle incremental cost of the AFV type divided by its life-cycle emission reductions. Thus, it is essential to estimate AFV life-cycle incremental costs and emission reductions. The calculation of AFV life-cycle incremental costs and emission reductions is presented below.

AFV Life-Cycle Incremental Costs

The calculation of AFV life-cycle incremental costs here takes into account initial vehicle purchase prices, expenditure on fuels, vehicle maintenance costs, the cost of inspection and maintenance (I/M) programs, and vehicle lifetime. Given the value difference of cost items occurring in different years, the present value (PV) of life-cycle costs is calculated by discounting future costs to present costs. The life-cycle incremental cost for a particular AFV type is the difference in the PV of life-cycle costs between the AFV type and baseline GVs. The PV of vehicle life-cycle costs is calculated with the equation below (note that cost items are presented as the costs to consumers in 1990 constant dollars throughout this paper):

$$PV_{cost} = IP + \sum_{i=1}^{n} [(FC_i + MC_i + Misc_i)/(1+r)^i]$$

where

PV_{cost} =	PV of vehicle life-cycle costs
IP =	Initial price of a new vehicle
n =	vehicle lifetime (years)
i =	vehicle age
FC_i =	annual fuel cost
MC_i =	annual vehicle maintenance cost
$Misc_i$ =	annual miscellaneous cost (such as the I/M cost)
r =	real-term discount rate (assumed 6% here)

Values adopted for the input parameters in the above equation are presented in Tables 1-4.

Table 1. Lifetime, Incremental Prices, and Fuel Economy Changes of AFV Types[a]

Vehicle Type	Lifetime (yr)	Incremental Price (1990 $)	MPG Increase (Energy Equiv.)
GV	12	N/A[b]	0%[c]
Methanol and Ethanol FFVs	12	300	5%
Dedicated MV	12	100	15%
Dual-Fuel LPGV	12	1,000	0%
Dual-Fuel CNGV	13	1,500	0%[d]
Dedicated CNGV	13	1,000	5%[d]
EV	15	Various[e]	N/A[f]

[a] Most values here are based on Wang et al. (1993).
[b] Not applicable. A retail price of $15,000 is assumed for GVs fueled with both conventional gasoline and RFG. RFG can be used in GVs without vehicle modification or design changes, though such modification or design changes for using RFG can certainly increase RFG emission-reduction benefits.
[c] An in-use fuel economy of 27 miles per gallon (MPG) is assumed for 1995 model-year compact gasoline cars. EPA shows a lab-tested fuel economy of 29.5 MPG for 1993 model-year compact cars under the 55/45 combined cycle (Murrell et al., 1993). In-use fuel economy is roughly about 10% less than lab-tested fuel economy for the combined cycle. Therefore, in-use fuel economy for 1993 model-year compact gasoline cars is about 26.6 MPG. It is assumed here that in-use fuel economy for the 1995 model year (the model year considered in this paper) is 0.4 MPG higher than that for 1993 model year and that the fuel economy of GVs fueled with RFG will be the same as that of GVs fueled with conventional gasoline on an energy-equivalent basis.
[d] It is assumed here that the lean burn strategy will not be used in CNGVs due to its problem with NO_x emission control.
[e] Incremental EV prices vary significantly with battery technology. EV batteries need to be replaced intermittently during the EV lifetime. Because of this, EV costs are calculated differently. Assumptions regarding EV battery performance and cost are presented in Table 4 below.
[f] Not applicable. EV per-mile electricity consumption is presented in Table 4 below.

Table 2. Annual VMT and Maintenance Costs of a Compact Gasoline Car[a]

Age (yr)	Annual VMT	Maintenance Cost[b] (1990 $)
1	12,900	132
2	12,600	289
3	12,300	368
4	11,900	415
5	11,500	447
6	11,000	468
7	10,600	477
8	10,100	488
9	9,600	488
10	9,100	489
11	8,700	86
12 and up	8,200	478

[a] From FHWA (1992).
[b] Including scheduled and unscheduled costs, and cost of engine oil changes. It is assumed here that vehicles with internal combustion engines (GVs, MVs, LPGVs, CNGVs, and ethanol vehicles) will have identical annual maintenance costs. Because of reliable electric motors and on-board electric systems, it is assumed here that EV annual maintenance costs will be 60% of the costs presented in the table.

Table 3. Prices and Energy Contents of Motor Fuels

Fuel	Price[a] ($/gal, or as noted)	Btu/gal[b] (based on low heating value)
Conventional Gasoline	1.30	115,000
RFG[c]	1.46	114,000
Pure Methanol	0.92	56,800
Ethanol	1.50[d]	76,000
LPG	0.95	84,000[e]
CNG	9.5[f]	N/A
Electricity	6.5[g]	N/A

[a] A federal road excise tax of $0.18 and a state road excise tax of $0.14 per gallon of gasoline equivalent are applied to each fuel. For detailed assumptions, see Wang et al. (1993).
[b] Except for compressed natural gas and electricity, energy contents of fuels are needed to convert gasoline-equivalent fuel economy to fuel economy of a particular fuel.
[c] California's phase 2 gasoline is assumed here.
[d] A blender's income tax credit equivalent to $0.60 per gallon of ethanol is excluded here. Although the credit is currently in effect, it is not clear whether it would stay if ethanol vehicles were mass-introduced. In addition, to level the playing field for various AFV types, the credit should be taken out, at least for a social evaluation of AFV cost-effectiveness.
[e] At a pressure of about 200 psi.
[f] Price is in $/$10^6$ Btu.
[g] Price is in cents per kilowatt-hour.

Table 4. Costs and Performance of EV-Related Components[a]

EV Price without Battery (as % of GV Price)	80
EV Electricity Consumption (kWh/mi)	0.4
Price per Battery ($)	9,375
Battery Life-Cycle VMT[b]	63,750
Home Recharging System Cost ($/yr)	32

[a] For detailed information, see Wang et al. (1993).
[b] VMT = vehicle-miles of travel.

An I/M program is assumed here for all internal combustion engine vehicle types but not for EVs, because EVs themselves do not produce emissions. The EPA has recently adopted an enhanced I/M program which requires that vehicles be tested as they are driven on chassis dynamometers (U.S. EPA, 1992). A biennial enhanced program with a cost per test of $40 is assumed here.

Note that CNGVs are assumed to last 13 years and EVs 15 years, while baseline GVs last for 12 years. To calculate life-cycle incremental costs for CNGVs and EVs, a second GV is assumed after the 12 years. The annualized cost of the second GV is considered together with the total cost of the first GV in calculating incremental costs of CNGVs and EVs.

AFV Life-Cycle Emission Reductions

In estimating AFV emission reductions, this paper includes vehicle exhaust and evaporative emissions of seven air pollutants — three criteria pollutants (non-methane organic gases [NMOG], carbon monoxide [CO], and nitrogen oxides [NO_x]) and four air toxic pollutants (benzene, 1,3-butadiene, formaldehyde, and acetaldehyde).

To be consistent with the PV of AFV life-cycle incremental costs, the PV of AFV life-cycle emission reductions is calculated by discounting annual AFV emission reductions. Annual emission reductions by a particular AFV type are estimated with annual emissions of baseline GVs and emission-reduction rates by AFV type, both of which are discussed below.

Annual Emissions of Baseline GVs. Annual emissions of baseline GVs are calculated with annual grams-per-mile emission rates and annual VMT. Grams-per-mile emission rates are estimated with Mobile5A for exhaust emissions of NMOG, CO, and NO_x and for evaporative emissions of NMOG. In using Mobile5A, an enhanced I/M program, federal Tier-I emission standards, and the Stage II technology to control refueling emissions in gasoline service stations are assumed.

GV air toxic emissions are calculated with Mobile5A-estimated NMOG emissions and a weighted distribution of each of the four air toxic pollutants in GV NMOG emissions (see Wang et al. [1993]).

Emission Reduction Rates by AFV Type. AFV emission reductions are affected by type of emission-control technologies installed on vehicles, designed tradeoffs between vehicle emissions and vehicle performance, and tradeoffs in emissions among different pollutants, all of which are influenced by desired AFV target emissions for meeting certain emission requirements. On the basis of data presented in Wang et al.'s study, a set of base-case AFV emission-reduction rates is assumed here (Table 5).

NMOG emission-reduction rates for the ten AFV types considered here are adjusted, with their ozone reactivity adjustment factors developed from maximum incremental reactivity (MIR) of individual HC species. Ozone reactivity adjustment factors can be developed from maximum ozone reactivity (MOR) of individual HC species. The MIR scale reflects atmospheric conditions in which small changes in HC concentrations have large effects on ozone formation. In contrast, the MOR scale reflects conditions in which ozone formation is primarily controlled by atmospheric NO_x concentration.

Emission-reduction rates by AFV type for some pollutants (see Table 5) are subject to great uncertainty. For example, EVs can increase or decrease NO_x emissions, depending upon the types of power plants used for generating electricity for EVs. MVs and CNGVs can increase or decrease NO_x emissions, depending on the emission-control strategies employed. Thus, the presented emission-reduction rates should be interpreted with caution.

This paper includes primary formaldehyde emissions from motor vehicles in estimating AFV formaldehyde emission impacts. Secondary formaldehyde emissions can be formed in the atmosphere from motor-vehicle tailpipe emissions. These secondary formaldehyde emissions are not included here.

Table 5. AFV Emission Reduction Rates (as percentage of GV emissions)

AFV Type	Exhaust Emissions							Evaporative Emissions[a]	
	NMOG[b]	CO	NOx	1,3-But.	Benzene	Formal.	Acetal.	NMOG[b]	Benzene
RFG[c]	-20	-20	0	-25	-25	20	0	-15	-25
M85 FFVs	-55	-10	-10	-80	-85	280	-75	-60	185
M100 FFVs	-60	-10	-10	-80	-85	245	-75	-75	-100
M85 Dedi. Vehicles	-65	-15	-10	-85	-90	195	-80	-85	10
M100 Dedi. Vehicles	-70	-20	-10	-85	-90	160	-80	-85	-100
E85 FFVs	-30	-10	-10	-80	-90	40	825	-40	185
Dual-Fuel LPGVs	-70	-30	0	-95	-95	15	-50	-100	-100
Dual-Fuel CNGVs	-90	-30	0	-95	-99	70	-65	-100	-100
Dedicated CNGVs	-90	-40	-10	-95	-99	40	-70	-100	-100
EVs	-95	-95	-60	-100	-100	-95	-100	-100	-100

[a] 1,3-Butadiene, formaldehyde, and acetaldehyde are absent in evaporative emissions. Therefore, evaporative emission-reduction rates are not applicable to these three air pollutants.
[b] These are NMOG emissions adjusted by the ozone reactivity adjustment factor for each fuel. NMOG emission reductions for MVs and ethanol vehicles are solely due to their lower reactivity adjustment factors. NMOG emission reductions for EVs are solely due to mass NMOG emission reductions. NMOG emission reductions for LPGVs and CNGVs are due to both mass NMOG emission reductions and lower reactivity adjustment factors.
[c] These are emission reductions of California's phase 2 reformulated gasoline, which were estimated by the California Air Resources Board (CARB, 1991).

Calculation of a Composite Tonnage of AFV Emission Reductions. With the above procedure and data, the PV of life-cycle AFV emission reductions is calculated for each of the seven pollutants. Cost-effectiveness of a particular AFV type can be calculated for each pollutant by allocating the incremental cost of the AFV type among the seven pollutants. Alternatively, a composite tonnage of emission reductions can be calculated from the emission reductions of the seven pollutants, and the cost-effectiveness of controlling the composite tonnage can be calculated for the AFV type. Because of the difficulty (sometimes impossibility) of allocating the incremental cost among the seven pollutants, this paper adopts the latter method.

The composite tonnage of emission reductions is calculated as the weighted-average of emission reductions for each of the seven pollutants. The following weighting factors developed by Wang et al. (1993) were used in calculating the composite tonnage: 1 for NMOG, 0.49 for CO, 1.40 for NO_x, 10 for benzene, 9.37 for 1,3-butadiene, 1.31 for formaldehyde, and 0.31 for acetaldehyde. The weighting factors for NMOG, CO, and NO_x were developed from the estimated emission values of the three pollutants in southern

California. The weighting factors for the four air toxics were developed from their estimated cancer risk factors and their residence time in the atmosphere.

AFV Emission-Control Cost-Effectiveness

Finally, AFV cost-effectiveness is calculated with the above-estimated AFV life-cycle incremental costs and emission reductions. The calculated AFV cost-effectiveness for each of the ten AFV types is presented in Figure 1.

As the figure shows, CNGVs are the most cost-effective AFV type in controlling emissions. In fact, the control cost of dual-fuel CNGVs is negligible. The control cost of dedicated CNGVs is negative, meaning that use of dedicated CNGVs actually results in net cost savings. Dual-fuel LPGVs, RFG, and dedicated methanol vehicles (both M85 and M100) are the next most cost-effective vehicle types. Control costs of these AFV types are between \$2,500 and \$4,000 per ton of emissions reduced. Methanol FFVs and EVs are less cost-effective, with control costs ranging from \$7,500 to \$10,000. E85 FFVs are the least cost-effective vehicle type, with a control cost above \$15,000.

Note that this ranking of the ten AFV types is according to their per-ton emission control costs, which indicate the cost to reduce one ton of emissions. The cost-effectiveness does not show what quantity of emissions an AFV type can reduce at the given cost. The per-vehicle monetary value of emission reductions will be calculated below for each AFV type. The per-vehicle emission reduction value explicitly indicates the total amount of emissions that each AFV type can reduce.

Caution must be taken in comparing the AFV cost-effectiveness calculated in this paper with that calculated in other studies. Whereas the cost-effectiveness in this paper is for a composite tonnage of emission reductions from seven pollutants, the cost-effectiveness in other studies may be for a specific pollutant (e.g., NMOG or NO_x).

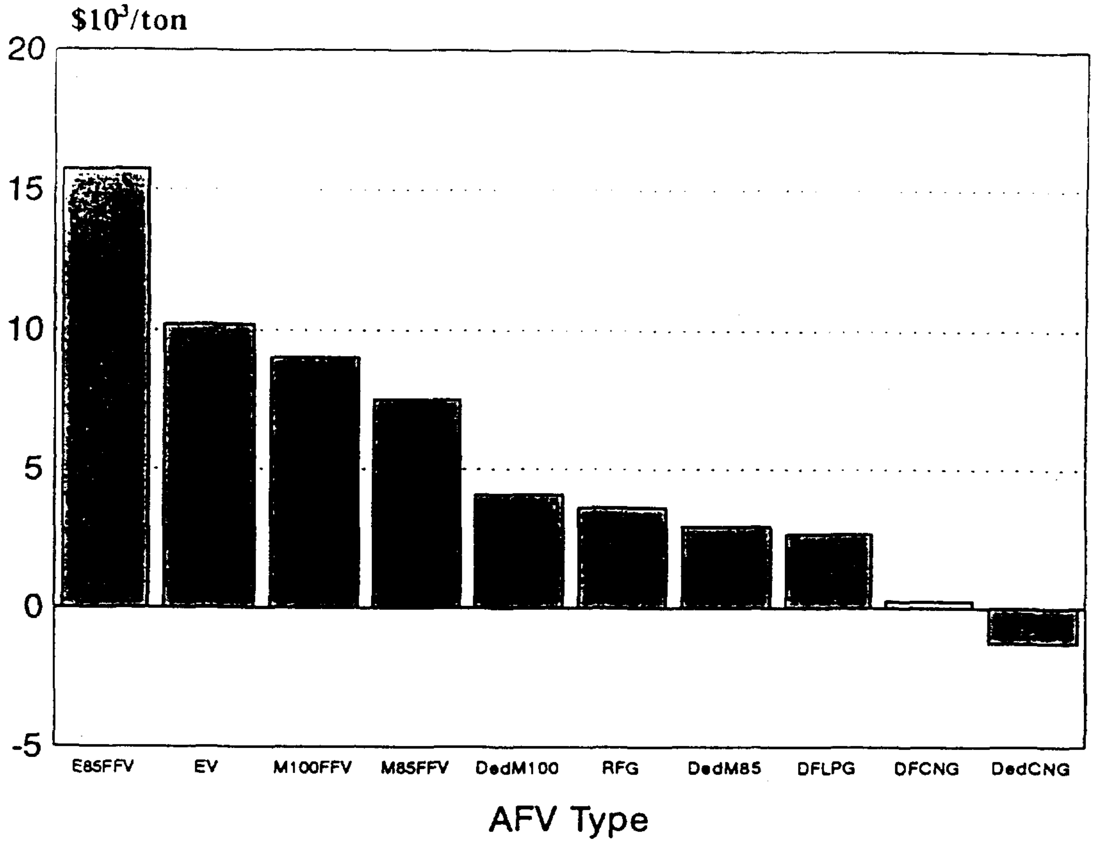

Figure 1. AFV Emission Control Cost-Effectiveness (for a composite tonnage, in 1990 $)

Sensitivity Analysis of AFV Emission-Control Cost-Effectiveness

The AFV cost-effectiveness presented in Figure 1 is based on the assumed values for cost and emission parameters affecting AFV cost-effectiveness. Changes in parameter values certainly cause changes in AFV cost-effectiveness. A sensitivity analysis is conducted below to assess the importance of major cost and emission parameters in determining the magnitude of AFV cost-effectiveness and to determine the plausible ranges of AFV cost-effectiveness.

Cases for the Sensitivity Analysis

AFV incremental prices, fuel prices, and emission reductions are subject to great uncertainties. These parameters have been demonstrated to be important in determining AFV cost-effectiveness. In the sensitivity analysis, three cases are established to represent these three parameters. For each case, a low value and a high value are assumed for each parameter. Tables 6 and 7 present cases representing AFV incremental prices and fuel prices. For the case representing AFV emission reductions, (1) a set of low AFV emission-reduction rates is calculated by assuming that AFV emissions are increased by 20% over the AFV emissions under the base-case AFV emission-reduction rates assumed in Table 5; and (2) a set of high AFV emission-reduction rates is calculated by assuming AFV emissions are decreased by 20% (for EVs, an emission-reduction rate of 100% is assumed for all pollutants, reflecting the fact that EVs generate zero tailpipe emissions).

Table 6. Sensitivity Analysis Case: AFV Incremental Prices (1990 $)

AFV Type	Low Value	High Value
Methanol and Ethanol FFVs	100	500
Dedicated MV	0	200
Dual-Fuel LPGV	800	1,200
Dual-Fuel CNGV	1,300	1,700
Dedicated CNGV	800	1,200
EV	USABC LG[a]	Lead/Acid[b]

[a] EV prices are essentially determined by battery costs. The long-term battery goal established by the U.S. Advanced Battery Consortium (USABC) is adopted here for the low EV price case. Wang et al. (1993) estimated a per-battery cost of $8,750 and a battery lifetime VMT of 170,000 for the USABC long-term goal (therefore, no battery replacement is needed during EV lifetime). The long-term goal has a high per-battery cost, but also high performance and long lifetime; therefore, vehicle life-cycle battery total cost is low.
[b] A lead/acid battery is adopted here for the high EV price case. A per-battery cost of $4,500 and a lifetime VMT of 27,000 are assumed for lead/acid battery. The lead/acid battery has a low per-battery cost, but also low performance and short lifetime; consequently, the EV life-cycle battery cost is high.

Table 7. Sensitivity Analysis Case: Fuel Prices ($/gal or as noted, 1990 $)

Fuel	Low Price	High Price
RFG	1.36	1.56
Methanol	0.82	1.02
Ethanol	1.20	1.80
LPG	0.75	1.20
CNG ($/$10^6$ Btu)	8.0	11.0
Electricity (cents/kWh)	4.5	8.5

Two additional cases are established to represent baseline GV emissions and air toxic emissions. One case assumes that actual on-road GV emissions are four times as great as the emissions estimated with Mobile5A for exhaust emissions of NMOG, CO, and air toxic pollutants. This case is based on the conclusion in a National Research Council study (National Research Council, 1991). The other case excludes emissions of the four air toxic pollutants in calculating AFV cost-effectiveness, which is intended to demonstrate the importance of air toxic pollutants in determining the magnitude of AFV cost-effectiveness.

Sensitivity Analysis Results

AFV cost-effectiveness was calculated for each of the cases established above. The calculated AFV cost-effectiveness is presented in Figure 2 (the numerical results of AFV cost-effectiveness are presented in an appendix table at the end of this paper).

Figure 2 shows dramatic impacts of changes in values for major cost and emission parameters on AFV cost-effectiveness. Except for CNGVs, whose cost-effectiveness shows little variation among the assumed cases, AFV cost-effectiveness varies widely for each AFV type. For ethanol and methanol FFVs, RFG, and dedicated methanol vehicles, the lowest control cost occurs for the on-road GV emission case, while the highest control cost occurs for the low emission-reduction cases. Cost-effectiveness varies from $4,500 to $38,700 for ethanol FFVs; from $2,500 to $15,000 for methanol FFVs (both M85 and M100); from $1,000 to $17,600 for RFG; and from $1,000 to $7,000 for dedicated methanol vehicles (both M85 and M100). Baseline GV emissions, AFV emission reductions, and fuel prices are the three important factors determining the cost-effectiveness of these AFV types.

Cost-effectiveness of EVs is generally around $10,000, except for two cases — the USABC long-term battery goal case and the on-road GV emission case. For the USABC long-term goal case, EVs have virtually zero control cost. For the on-road GV emission case, EV control cost is about $3,000.

The control cost of dual-fuel LPGVs ranges from virtually zero for the low-fuel-price case to $6,000 for the high-fuel-price case, meaning that LPG price is the predominant factor determining LPGV control cost.

The ranking of the ten AFV types according to their cost-effectiveness remains essentially unchanged for each of the cases. That is, CNGVs are the most cost-effective vehicle type; methanol and ethanol FFVs are the least cost-effective vehicle types; and RFG, EVs, dedicated methanol vehicles, and dual-fuel LPG vehicles fall in between. However, there are two exceptions. The first exception is that RFG for the low AFV emission-reduction case can become as expensive as methanol FFVs. The second exception is that EVs with the USABC long-term battery goal can become as cost-effective as CNGVs.

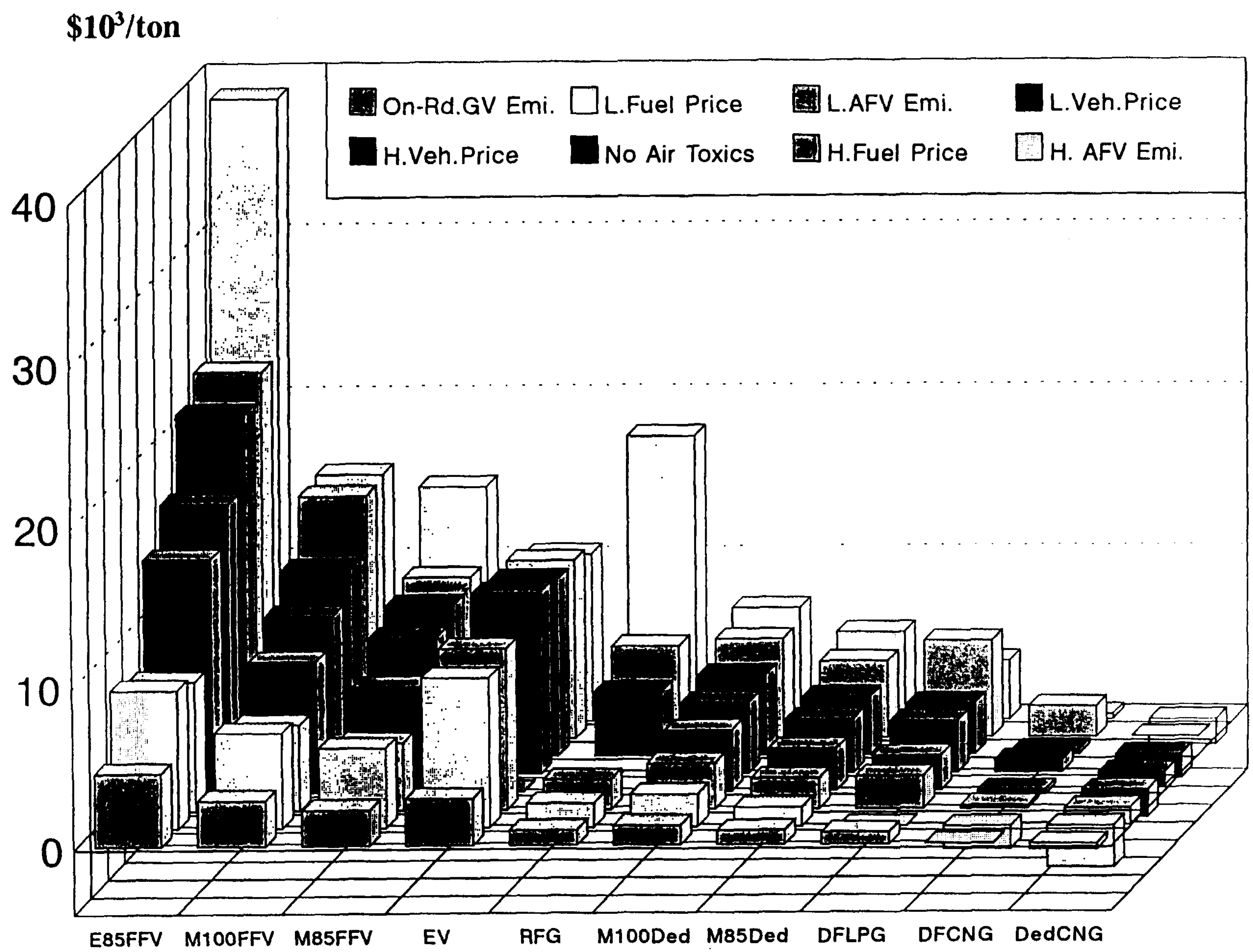

Figure 2. AFV Emission Control Cost-Effectiveness for Eight Cases

Per-Vehicle Monetary Value of AFV Emission Reductions

In this section, per-vehicle monetary values of AFV emission reductions are calculated from dollars-per-ton emission values and tons of emissions reduced over the AFV's lifetime.

Dollars-per-Ton Emission Values

The dollar value of emissions can be calculated by means of two general methods — a damage estimate method and a control cost estimate method. The damage estimate method estimates dollar values of the damages created by emissions. The method requires estimation of the physical impacts of emissions, such as health and welfare impacts, and the valuation of the estimated impacts. Estimation of physical impacts relies on emission estimates, simulation of emission transport, estimated exposure of receptor populations, and establishment of dose/response relationships for those populations. Valuation of physical impacts can be difficult and controversial.

The control cost estimate method estimates emission control costs of some given control measures. The estimated control costs are then treated as the monetary opportunity benefits of the emissions reduced by other control measures.

Table 8 summarizes imputed values of eliminating one ton of emissions for three criteria pollutants (VOC, CO, and NO_x,) as presented in several studies. As can be seen from the table, the emission values based on the damage estimate method are consistently lower than those based on the control cost estimate method. However, because of great uncertainties involved in the damage estimate method, this result by no means indicates that current emission standards lead to excess control of emissions.

Table 8. Summary of Imputed Emission Values ($/ton in 1990 $[a])

Study	Imputed Value	Estimating Method	Target Region
		VOC:	
Bernow et al. (1990)	5,570	Control cost	Ozone non-attainment areas
	30,450	Control cost	Southern California
CEC (1993)	7,280	Damage estimate	South Coast air basin
	19,920	Control cost	South Coast air basin
Chernick et al. (1991)	3,700	Control cost	California
	340	Control cost	Out-of-California
	5,570	Control cost	Massachusetts
Wiel (1991)	1,240	Control cost	Nevada
So. Calif. Gas (1991)	3,640	Control cost	South Coast air basin
So. Calif. Edison (1991)	2,760	Damage estimate	South Coast air basin
	19,450	Control cost	South Coast air basin

CO:			
Bernow et al. (1990)	860	Control cost	Urban areas
CEC (1993)	3	Damage estimate	South Coast air basin
	9,800	Control cost	South Coast air basin
Chernick et al. (1991)	900	Control cost	Massachusetts
Wiel (1991)	970	Control cost	Nevada
So. Calif. Gas (1991)	200	Control cost	California
NOx:			
Bernow et al. (1990)	6,830	Control cost	Northeast U.S.
	275,100	Control cost	Southern California
CEC (1993)	15,270	Damage estimate	South Coast air basin
	27,830	Control cost	South Coast air basin
Chernick et al. (1991)	13,190	Control cost	California
	3,070	Control cost	Out-of-California
	6,830	Control cost	Massachusetts
	1,870	Damage estimate	New York
	1720	Damage estimate	Unspecified
Wiel (1991)	7,140	Control cost	Nevada
So. Calif. Gas (1991)	12,790	Control cost	South Coast air basin
So. Calif. Edison (1991)	4,780	Damage estimate	South Coast air basin
	27,160	Control cost	South Coast air basin

[a] The cited studies presented emission values in constant or current dollars of various years. The emission values have been converted into 1990 constant dollars via the consumer price index. Emission values estimated by CEC were presented in $/ton/year. It was determined, by checking the original data sources from which CEC derived its estimates and CEC's adjustments to value estimates, that CEC's estimates were actually in $/ton.

Table 8 suggests that emission values estimated for California are much higher than those for other regions. To reflect the difference in emission values between California and elsewhere, two sets of values are adopted in this paper: one set for California, and another for other U.S. regions (Table 9). In the determination of emission values for each set, those values estimated by the control cost estimate method were given primary consideration.

Table 9. Emission Damage Values for California and Elsewhere ($/ton, 1990 $)

Pollutant	Emission Value	
	California	Other U.S. Regions
NMOG	20,000	5,000
CO	5,000	950
NOx	26,000	7,000

The four air toxic pollutants are classified as carcinogens, and their most damaging effect is resultant cancer incidence. Wang et al. (1993) assumed damage factors for the four toxic pollutants relative to NMOG. The assumed damage factors are 10 for benzene, 9.37 for 1,3-butadiene, 1.31 for formaldehyde, and 0.31 for acetaldehyde. These factors, together with the NMOG emission values in Table 9, were used to determine emission values for each air toxic pollutant.

Present Value of AFV Life-Cycle Emission Reductions

The present value (PV) of life-cycle emission reductions by AFV type is calculated by discounting annual emission reductions by the AFV type over its lifetime. Annual AFV emission reductions are, in turn, calculated from annual baseline GV emissions and from AFV emission-reduction rates. The method and assumptions for calculating AFV emission reductions have been presented above.

It is believed that actual on-road NMOG and CO exhaust emissions from GVs are two to four times higher than the emissions estimated with models developed by the EPA or the California Air Resources Board (National Research Council, 1991). The sensitivity analysis discussed above showed that baseline GV emissions are important in determining AFV cost-effectiveness. Because of the uncertainty and the importance of baseline GV emissions, two sets of these emissions are assumed here: one uses the GV emissions estimated with Mobile5A; the other uses the Mobile5A-estimated GV emissions multiplied by a factor of four for the exhaust emissions of NMOG, CO, and air toxics.

Per-Vehicle Dollar Value of AFV Emission Reductions

The per-vehicle dollar value of emission reductions by AFV type is calculated by multiplying total emission reductions by the AFV type with dollars-per-ton emission values. Calculated emission-reduction values are presented in Table 10. As the table shows, four sets of AFV emission-reduction values are calculated from the two sets of imputed emission values (California and non-California values) and the two sets of baseline GV emissions (Mobile5A-estimated and on-road adjusted GV emissions).

Per-vehicle AFV emission reductions can be worth thousands to tens of thousands of dollars, depending on vehicle types and assumptions about per-ton emission values and baseline GV emissions. Among the ten AFV types, EVs have the highest emission-reduction values; CNGVs and LPGVs have the next-highest values; dedicated methanol vehicles are next; methanol FFVs have low values; and RFG and E85 FFVs have the lowest values. The magnitude of the emission-reduction values reflects the magnitude of per-vehicle emission reductions. That is, EVs have the largest amount of total emission reductions, while RFG and E85 FFVs have the smallest amount of total emission reductions.

Per-vehicle emission-reduction values are very different with per-ton emission values and baseline GV emissions. Between the lowest value (combination of the non-California emission values and Mobile5A-estimated GV emissions) and the highest value (the combination of the California emission values and on-road adjusted GV emissions), the per-vehicle emission-reduction value for a given AFV type can be changed by more than a factor of 12.

Table 10. PV of Per-Vehicle Dollar Value of AFV Emission Reductions

$/ton Value	Non-California Values		California Values	
GV Emissions	Mobile5A-Estimated	On-Road Adjusted	Mobile5A-Estimated	On-Road Adjusted
RFG	460	1,700	2,170	8,110
M85 FFV	800	2,590	3,340	10,970
M100 FFV	920	2,770	3,800	11,720
M85 Dedicated	1,030	3,200	4,330	13,750
M100 Dedicated	1,140	3,570	4,850	15,550
E85 FFV	660	2,200	2,790	9,440
Dual-Fuel LPGV	1,260	4,160	5,540	18,600
Dual-Fuel CNGV	1,360	4,570	5,900	20,240
Dedicated CNGV	1,550	5,170	6,840	23,260
EV	2,740	8,740	12,430	41,200

Per-vehicle emission-reduction values in Table 10 are attributable to emission reductions for each of the seven pollutants. (Note that emissions of some air toxic pollutants may be increased by certain AFV types, contributing to decreases in per-vehicle emission reduction values. See Table 5 for the air toxic increases by certain AFV types.) The contribution of each air pollutant to emission-reduction values varies among the ten AFV types. The order of the pollutants, in terms of the significance of their contributions, is CO, NMOG, benzene, and 1,3-butadiene for RFG; NMOG, benzene, CO, and NO_x for methanol and ethanol vehicles; NMOG, CO, benzene, and 1,3-butadiene for LPGVs and CNGVs; and CO, NMOG, benzene, and NO_x for EVs.

Magnitude of Vehicle or Fuel Subsidies Based on AFV Emission-Reduction Values

Life-cycle costs for most AFV types are higher than those for baseline GVs. The higher life-cycle costs for RFG, methanol, and ethanol vehicles are predominantly caused by increases in per-mile fuel costs. The higher life-cycle costs for LPGVs, CNGVs, and EVs are caused by increases in vehicle initial prices. To encourage use of AFVs for curbing air pollution problems, price subsidies equal to dollar values of AFV emission reductions need to be provided to AFV users.

Two types of AFV subsidies can be designed — vehicle price subsidies and fuel price subsidies. It is commonly assumed that vehicle initial prices affect the purchasing choice of vehicle types and that fuel prices affect vehicle usage. To encourage the purchase of LPGVs, CNGVs, and EVs, subsidies to vehicle initial prices need to be provided for these vehicle types (battery subsidies could be designed for EVs to reduce battery-replacement costs). The per-vehicle price subsidies for these vehicle types can be set equal to the dollar value of their emission reductions.

Per-mile fuel costs for methanol and ethanol vehicles and for RFG are higher than those for GVs fueled with conventional gasoline. It is proposed here that fuel price subsidies be applied to these AFV types. For FFVs, high methanol and ethanol costs relative to gasoline on a per-mile basis may encourage vehicle users to switch from methanol and ethanol to gasoline, resulting in no emission reduction benefits from FFVs. Price subsidies on methanol and ethanol can prevent such a fuel switch. It is proposed that the fuel price subsidies for these AFV types be at the level where life-cycle fuel price subsidies will be equal to per-vehicle emission-reduction values.

Table 11 presents the estimated fuel price subsidies for RFG, methanol, and ethanol vehicles and vehicle price subsidies for LPGVs, CNGVs, and EVs. As the table shows, the amount of fuel or vehicle subsidies based on AFV emission-reduction values is substantial. In fact, with California emission values and on-road adjusted GV emissions, fuel subsidies or vehicle subsidies are far greater than fuel prices, or even vehicle prices themselves. To actually provide these amounts of subsidies may be unrealistic. However, because these subsidies were calculated relative to conventional GVs, conventional gasoline vehicles could be taxed at their emission damage values, and use of AFVs would have relative advantages even without subsidies.

Table 11 shows four different methanol price subsidies for a given case, depending on the type of methanol vehicle (i.e., M85 FFVs, M100 FFVs, M85 dedicated, and M100 dedicated). In reality, it would be impossible to differentiate methanol price subsidies based on methanol vehicle types. For practical purposes, the average of the four methanol price subsidies may need to be adopted.

Table 11. Vehicle and Fuel Price Subsidies for Alternative-Fuel Vehicles

$/ton Value	Non-California Value		California Value	
GV Emissions	MB5-Estimated	On-Road Adj.	MB5-Estimated	On-Road Adj.
Fuel Price Subsidy (cents/gal)				
RFG	13	47	59	222
Methanol (based on M85 FFV)	16	50	65	213
Methanol (based on M100 FFV)	13	40	54	168
Methanol (based on M85 dedic.)	22	68	92	393
Methanol (based on M100 dedic.)	18	56	76	243
Ethanol (based on E85 FFV)	16	54	68	229
Vehicle Price Subsidy ($/vehicle)				
Dual-Fuel LPGV	1,260	4,160	5,540	18,600
Dual-Fuel CNGV	1,360	4,570	5,900	20,240
Dedicated CNGV	1,550	5,170	6,840	23,260
EV	2,740	8,740	12,430	41,200

Providing the amounts of fuel or vehicle price subsidies estimated above for AFVs would reduce life-cycle AFV costs substantially. Table 12 presents the AFV life-cycle cost changes with inclusion of vehicle or fuel price subsidies. As the table shows, use of most AFV types now in fact leads to net cost savings for the case with California emission values or the case with non-California emission values but on-road GV emissions. Net cost savings vary among the ten AFV types. The greatest cost savings, over $30,000 per vehicle, occur for EVs for the case with California emission values and on-road adjusted GV emissions. The results imply that, by taking into account AFV emission-reduction values, use of AFVs in California (where the worst air pollution problems occur) will probably make economic sense. In other U.S. regions, if one believes that actual on-road GV emissions are much higher than estimated, use of all AFV types except E85 FFVs will make economic sense.

Table 12. Changes in AFV Life-Cycle Costs with Inclusion of Vehicle or Fuel Subsidies (relative to GV life-cycle costs)

$/ton Value	Non-California Value		California Value	
GV Emissions	Mobile5A-Estimated	On-Road Adjusted	Mobile5A-Estimated	On-Road Adjusted
RFG	170	-1,070	-1,540	-7,480
M85 FFV	710	-1,080	-1,830	-9,460
M100 FFV	1,110	-750	-1,780	-9,700
M85 Dedicated	-240	-2,410	-3,540	-12,960
M100 Dedicated	120	-2,310	-3,590	-14,290
E85 FFV	2,060	520	-70	-6,720
Dual-Fuel LPGV	-260	-3,160	-4,540	-17,600
Dual-Fuel CNGV	-1,260	-4,470	-5,800	-19,240
Dedicated CNGV	-2,150	-5,770	-6,940	-23,860
EV	6,910	910	-2,770	-31,550

In calculating AFV subsidies, this paper accounts for AFV emission-reduction benefits only. AFVs may have other social benefits, such as reductions in CO_2 emissions and increases in energy security achieved by diversifying energy sources for the transportation sector (however, use of RFG may not achieve energy security benefits). Providing the subsidies reflecting these benefits would certainly make AFVs even more attractive.

Conclusions

The estimated emission-control cost-effectiveness of ten AFV types shows that CNGVs are the most cost-effective AFV type in controlling air-pollutant emissions; E85 FFVs are the least cost-effective AFV type; and methanol vehicles, LPGVs, and EVs fall in between. A sensitivity analysis of various cases representing changes in values for major cost and emission parameters has suggested that the cost-effectiveness of CNGVs changes very little; they are always the most cost-effective vehicle type. Cost-effectiveness of other vehicle types can change dramatically with changes in values for major cost and emission parameters. However, the ranking of the ten AFV types according to their cost-effectiveness remains essentially unchanged, except that under certain circumstances (i.e., high fuel costs, low emission reductions), ethanol and methanol FFVs and RFG could become very expensive.

Per-vehicle dollar values of emission reductions are estimated to be significant. Fuel or vehicle price subsidies that are equal to emission-reduction values can change AFV life-cycle costs dramatically. In fact, providing the fuel and vehicle price subsidies estimated in this paper for AFVs would change most AFV types from net cost increases to net cost decreases.

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Appendix: AFV Emission-Control Cost-Effectiveness for Various Cases ($/ton)

AFV Type	Base Case	Case 1: AFV Prices		Case 2: Fuel Prices		Case 3: AFV Emission Reductions		Case 4: On-Road GV Emissions	Case 5: No Air Toxics
		Low	High	Low	High	Low	High		
RFG	3,620	N/A	N/A	1,510	5,730	17,660	1,850	940	3,990
M85 FFV	7,520	6,530	8,520	4,950	10,090	14,580	4,170	2,220	9,450
M100 FFV	9,030	8,130	9,920	5,900	12,150	15,380	5,310	2,820	11,730
M85 Dedic.	2,940	2,600	3,350	1,210	4,740	5,470	1,890	890	3,640
M100 Dedic.	4,090	3,760	4,410	2,020	6,160	7,010	2,820	1,210	5,000
E85 FFV	15,730	14,570	16,890	8,570	22,890	38,670	8,010	4,510	21,340
DF LPGV	2,680	2,150	3,220	30	6,000	3,640	2,010	760	3,210
DF CNGV	250	-270	760	-1,420	1,910	320	190	70	290
Dedic. CNGV	-1,270	-1,700	-850	-2,580	40	-1,590	-1,040	-360	-1,470
EV	10,200	50	11,306	9,270	11,120	10,410	10,000	2,890	11,000